5

Shock-Metamorphosed Rocks (Impactites) in Impact Structures

5.1. ROCK TYPES IN THE FINAL IMPACT STRUCTURE

A wide variety of distinctive rock types — breccias, melts, and shock-metamorphosed target rocks — are produced during formation of impact structures. The classification of these complex and diverse rocks is an active and much-debated activity (see below). However, the general term **impactite** is used here as a convenient overall designation for all rocks affected by, or produced by, the shock waves and other processes generated by hypervelocity meteorite impact events.

Different varieties of impactites are produced at different times during the impact process, and they occur in different locations beneath, within, and around the final impact structure. The diverse features of impactites reflect, in varying ways, different aspects of the impact event itself: (1) the initial shock-wave distribution around the impact point; (2) the subsequent excavation flow, formation of the transient crater, and ejection of material from it; (3) the crater modification processes. The general model described below will be modified, in actual impact structures, by such individual factors as the target lithology, stratigraphy, and the nature and impact angle of the projectile, but the model provides a general basis for the identification and classification of impactites (see also *Dence,* 1968; *Grieve,* 1991; *Stöffler et al.,* 1988).

The basic distribution of shock-wave pressures around the impact point is largely established by the end of the contact/compression stage. The expanding shock waves deposit energy continuously in the target rocks through which they pass, and both their peak pressures and the resulting post-shock temperatures drop rapidly with distance from the impact point. As the contact/compression stage ends, and the transient crater begins to form, the zones of shock pressure form a series of approximately hemispherical shells around the impact point, with the peak shock pressure decreasing rapidly outward (Fig. 3.2).

During the subsequent excavation stage and formation of the transient crater, virtually all the target rock exposed to shock pressures of ≥25–30 GPa, which now consists of a mixture of vapor, superheated rock melt, and coherent but highly shocked target rock, is broken up and accelerated outward (*Dence,* 1968; *Dence et al.,* 1977; *Grieve and Cintala,* 1981). Because the excavation flow lines cut across the originally hemispherical shock-pressure zones (Fig. 3.4), the excavated material will consist of a mixture of target rocks subjected to widely differing shock pressures and showing a wide range of shock effects. A melt-rich portion flows downward and outward from the center to form a coating along the floor and walls of the growing crater (*Grieve et al.,* 1977). The remainder, a mixture of rock fragments and smaller bodies of melt, is impelled outward from the center of the cavity. Much of this material may be entirely ejected from the transient crater; some may remain within the crater as a unit of mixed rubble and melt above the fractured crater floor.

The subcrater rocks beneath the zone of excavation are subjected to lower shock pressures (≤30 GPa), and the dominant effects produced are shatter cones, brecciation, and in-place fracturing. As the upper part of the target rocks are excavated from the transient crater, these rocks are displaced downward, more or less coherently, to form the floor of the transient crater and the zone of **parautochthonous** rocks beneath it.

The final modification of the transient crater into a simple or complex impact structure involves several distinct gravity-related processes that influence the distribution of impactite units: (1) rapid relative movements of large blocks of subcrater target rocks downward, inward, and upward along relatively narrow faults; (2) collapse of oversteepened crater walls into the crater cavity; (3) deposition of a minor amount of ejected material within the crater. The first process may create additional breccias and related rock types beneath the crater. The other two processes produce a large portion of the **crater-fill deposits,** which are characterized by a generally fragmental character and the presence of shock-metamorphic effects that range from simple fracturing to complete melting.

5.2. CLASSIFICATION OF IMPACTITES

The definition and classification of impact-produced materials, both individual rock fragments and large formations, is a complex, longstanding, and difficult subject (for details, see *Stöffler,* 1971; *Stöffler et al.,* 1979; *Taylor et al.,* 1991; *Stöffler and Grieve,* 1994, 1996; *Reimold,* 1995). No attempt will be made here to develop a complete and unanimously acceptable system. The simplified system presented here emphasizes field and petrologic characteristics and is based, as far as possible, on objective features that are observable in outcrop, hand specimen, and thin section. This classification also uses, as much as possible, traditional terms already applied to equivalent rocks (e.g., breccias, melt rocks) formed by common geological processes. Although this system is generally consistent with more detailed classifications (e.g., *Stöffler and Grieve,* 1994), it is restricted to terrestrial rock types produced in single impact events and does not consider the special complexities of cratering on other planets, including the effects of multiple impacts or the absence of an atmosphere (see *Taylor et al.,* 1991; *Stöffler and Grieve,* 1994, 1996).

The term **impactite** is used here to designate all rocks produced during an impact event, including shock-metamorphosed (but still recognizable) target rocks (both in place and as fragments in breccias), breccias, and impact melts. Under this umbrella, the classification and terminology of impactite formations are based on a few key features: location with respect to the crater, source(s) of component materials, and lithologic characteristics (Table 5.1).

More detailed discriminators, used in other classifications, include (1) particle sizes and size ranges; (2) relative percentages of components in breccias, e.g., ratios of fragments/matrix, and lithic/glassy fragments; (3) shock-metamorphic effects in individual breccia fragments (both the shock level in individual fragments and the range of shock effects in multiple fragments); and (4) textures and crystallinity of melt rocks.

In earlier discussions of impactites and the cratering process (*Dence,* 1965, 1968; *Grieve,* 1991), a fundamental and useful distinction has been made between the **parautochthonous rocks** beneath the crater floor and the **allogenic** (or **allochthonous)** units (breccias and melt rocks) that fill the crater **(crater-fill units)** and form the units of **ejecta** outside it (Figs. 3.7 and 3.13). The observed characteristics of these different rock types are frequently distinctive enough that they can be distinguished, even in isolated hand specimens or outcrops.

The **parautochthonous** rocks beneath the crater have remained relatively coherent during crater formation, although they have been deformed and displaced. These rocks, which correspond to the lower **displaced zone** of the transient crater, are subjected to relatively lower shock pressures, and observed shock-deformation effects are generally limited to fracturing, brecciation, and the formation of shatter cones, although higher-pressure mineral-deformation features may be developed in a relatively small volume beneath the crater floor. The **allogenic** rocks, chiefly breccias and melts, that fill the crater and make up the ejecta beyond the crater rim, are characterized by a more diverse lithology, a fragmental or melted character, and a wide range of observed shock effects. In particular, the **crater-fill breccias** are a complex mixture of materials with different histories of shock pressures and transport: unshocked rocks derived from the distant parts of the crater rim and walls, more highly shocked and melted fragments excavated from the transient crater and redeposited, and large and small bodies of impact-generated melt.

The following sections discuss impactites on the basis of location with respect to the impact structure: (1) *subcrater:* parautochthonous rocks, cross-cutting allogenic units, and pseudotachylite; (2) *crater interior:* allogenic crater-fill deposits (lithic breccias, suevite breccias, and impact melt breccias); (3) *crater rim region:* proximal ejecta deposits; (4) *distant from crater:* distal ejecta. A detailed discussion of impact melt rocks in these different environments is provided in Chapter 7.

5.3. SUBCRATER ROCKS

5.3.1. Formation Conditions

During formation of the transient crater, the rocks located in the **displaced zone** below the zone of excavation are driven downward and outward, more or less coherently (Fig. 3.4), but they are not completely broken up or excavated. Instead, they are deformed, thinned, and moved downward and outward as the transient crater forms, and then (in the central parts of larger structures) rapidly elevated as the central uplift forms (*Dence,* 1968; *Dence et al.,* 1977; *Kieffer and Simonds,* 1980; *Grieve and Cintala,* 1981; *Grieve et al.,* 1981; *Stöffler et al.,* 1988).

During these movements, the subcrater rocks are generally displaced as large individual blocks typically tens to hundreds of meters (or even larger) in size. However, adjacent regions within this zone may display little displacement relative to each other, and original stratigraphy and structural features may be well preserved within individual blocks. The term **parautochthonous** has therefore been applied to these rocks to indicate their general relative coherence.

The shock pressures imposed on the parautochthonous rocks vary widely because of the complex relationship be-

TABLE 5.1. Criteria for impactite classification.

1. Location with respect to crater (R_c = crater radius)

Crater Floor and Subcrater	Within Crater	Crater Rim and Near-Surface
Parauthochtonous rocks:	**Allogenic** rocks:	**Allogenic** rocks:
target rocks (coherent)	**Crater-fill deposits**	**Ejecta:**
lithic breccias	(= crater-fill breccias)	**proximal** (<5 R_c)
	(= "breccia lens")	**distal** (>5 R_c)
Allogenic rocks (cross-cutting)	**lithic breccias**	
breccia dikes	melt-bearing breccias	
impact melt dikes	**suevites**	
	impact melt breccias	
Pseudotachylite	(= melt-matrix breccias)	
	impact melt rocks	

2. Sources of component materials

Parautochthonous rocks	**Allogenic** rocks
Approximately in place (local). Original stratigraphy and structure (largely) preserved.	Derived from single or multiple sources elsewhere.

3. Breccia characteristics

a. Fragment character	**Lithic breccia** Rock/mineral fragments only	**Suevite** (breccia) Melt/glass fragments present Rock/mineral fragments
b. Fragment lithology	**Monomict** (breccia) Single rock type	**Polymict** (breccia) Multiple rock types
c. Matrix character	**Clastic-matrix** (breccia) Discrete fragments	**Impact melt breccia** (= melt-matrix breccia) Coherent melt (glassy or crystalline)

4. Melt rock character (standard geological terms)

Holohyaline (glassy) **Hypocrystalline** (mixed glassy/crystalline) **Holocrystalline** (completely crystalline)	For grain size, texture, etc., use other standard igneous rock discriminators, e.g.: **Microcrystalline** **Porphyritic** **Trachytic,** etc.

tween the original shock-wave distribution and the subsequent crater modification. Shock pressures in the parautochthonous rocks are therefore highest near the center of the structure and decrease rapidly outward toward the margin. Along the floor of the transient cavity (approximately the floor of the final crater), shock pressures may exceed 25–30 GPa in the center, decreasing to ≤2 GPa at the rim, the minimum pressure needed to excavate material from the transient crater (*Grieve and Robertson,* 1976; *Robertson and Grieve,* 1977; *Kieffer and Simonds,* 1980; *Dressler et al.,* 1998). Shock pressures also drop off rapidly with increasing depth below the crater floor. In the center, pressures typically drop from about 25–30 GPa to a few GPa over distances of less than a few hundred meters in small structures (*Dence et al.,* 1977; *Grieve et al.,* 1981) and over no more than a few kilometers in larger ones (*Stöffler et al.,* 1988).

5.3.2. In-Place Shock-Metamorphosed Rocks

The shock effects preserved in the parautochthonous subcrater rocks therefore reflect a wide range of shock pressures. In a small region immediately below the central part of the crater floor (i.e., at the base of the excavation zone), pressures of 10–30 GPa produce distinctive microscopic deformation effects in quartz and feldspar, while creating postshock temperatures of ≤300°C. In smaller impact structures, this zone of identifiably high shock pressures is less than a few hundred meters thick, partly because of the rapid decay of the original shock wave with distance from the impact point, and partly because of the subsequent compression, thinning, and displacement of the subcrater rocks during transient crater formation (*Dence et al.,* 1977; *Grieve and Cintala,* 1981). Beneath this zone, lower shock pressures (possibly 2–6 GPa) produce distinctive megascopic deformation features (shatter cones) in a deeper region near the center of the crater.

Shock pressures over most of the zone of parautochthonous rocks are too low (≤2 GPa) to produce distinctive shock-deformation effects, but they are high enough to exceed the yield strengths of near-surface crustal rocks (typically <1–2 GPa; *Kieffer and Simonds,* 1980). As a result, large volumes of rock beneath the crater floor are broken and crushed during the early stages of crater formation, producing units of in-place lithic breccia that generally lack distinctive high-pressure shock-metamorphic effects. At the same time, and subsequently, larger fractures that develop in this zone may be intruded by allogenic materials (rock fragments and/or melt) to form cross-cutting dike-like bodies (e.g., *Lambert,* 1981; *Bischoff and Oskierski,* 1987; *Dressler and Sharpton,* 1997).

The parautochthonous rocks below the crater may also be strongly affected by subsequent large-scale movements during the crater modification stage. Such movements may produce equally striking but different breccias. In large structures, where modification involves the development of a central uplift, deep-seated parautochthonous rocks may be suddenly uplifted for distances of hundreds of meters to several kilometers. This uplift may bring distinctively shocked rocks (e.g., containing shatter cones) to the surface, where they may provide definite evidence for the impact origin of a large structure. However, these rapid movements may also generate additional varieties of breccias and destroy the original spatial relations of the parautochthonous rocks to each other, making the geology and history of the structure more difficult to decipher.

Understanding the variety of breccias in subcrater rocks is complicated by several factors (e.g., *Lambert,* 1981; *Bischoff and Oskierski,* 1987; *Dressler and Sharpton,* 1997). Breccias may form at various stages in the cratering process: (1) during the initial shock-wave expansion and transient crater formation; (2) during the subsequent modification of the transient crater, including (in large structures) movements associated with the rise of the central uplift and peripheral collapse around the rim. Even within the brief formation time of an impact crater, it is possible for multiple generations of breccia to develop and to produce distinctive cross-cutting relations, even though the time between one breccia generation and the next may be measured in seconds or minutes (*Lambert,* 1981; *Bischoff and Oskierski,* 1987; *Dressler and Sharpton,* 1997). Another problem is melt formation; rocks can be shock-melted by the initial impact and then distributed as melts or melt-bearing breccias throughout the crater basement, but rocks can also be melted subsequently by friction generated during the rapid movements of large volumes of rock involved in crater modification and central uplift formation.

5.3.3. Lithic Breccias (Parautochthonous)

Impactite breccias that form by the shattering and pulverizing of target rock essentially in place (*autoclastic*) typically form irregular bodies tens to hundreds of meters in size, which show gradational contacts against areas of similar but more coherent target rocks. These **lithic breccias** are composed entirely of rock and mineral fragments in a **clastic matrix** of smaller, but similar, fragments. Fragments tend to be angular to sharp, although fragments of softer rocks like carbonates and shales may be well rounded. The breccias themselves tend to be poorly sorted. The fragments are derived from local target rocks, and the breccias may be monomict or polymict, depending on the lithologic variety present in the nearby target rocks. Distinctive shock-metamorphic effects (e.g., PDFs in quartz) are generally absent in the fragments. The breccias show no evidence of significant transport, and they contain no exotic fragments or glassy material.

These rocks often resemble breccias formed by more normal geological mechanisms such as volcanic explosions or tectonic movements, and their identification as impact products is often difficult and uncertain. In general, the subcrater regions of impact structures display highly localized and variable deformation over short distances, a close association of different kinds of breccias developed from basement rocks, and the presence of allochthonous dike-like bodies of breccia and melt. This variability in deformation and rock types contrasts with the more uniform or gradational effects produced by endogenic mechanisms. Even so, identification of these rocks as impact breccias can generally not be done directly, but depends on demonstrating their association with more highly shocked rocks whose impact origin is clear (e.g., *French et al.,* 1997).

5.3.4. Cross-Cutting (Allogenic) Breccias

Other bodies of breccia in the subcrater rocks contain significant amounts of material that have clearly been introduced into them from elsewhere, and they are therefore considered here as **allogenic breccias.** These bodies tend to have more regular shapes and to show sharp contacts and clear cross-cutting relations against the subcrater rocks. Such breccias often occur as distinctive **breccia dikes**, which typically range from less than a meter to tens of meters in width and may be as much as a kilometer long (*Lambert,* 1981; *Bischoff and Oskierski,* 1987; *Dressler and Sharpton,* 1997). These bodies contain fragments of target rock that are angular to rounded and range in size from <1 mm to several meters. These breccias tend to be **polymict,** with lithologically diverse fragments, indicating mixing over distances of at least several hundred meters. In addition, they frequently contain significant amounts of allogenic material, such as fragments from even more distant rock units. This allogenic material is frequently derived from more central regions of the crater, often from *above* the present location of the dike, and it often consists of distinctive highly shocked rock fragments or melt.

A wide variety of such cross-cutting breccias has been reported from several impact structures (*Lambert,* 1981; *Bischoff and Oskierski,* 1987; *Dressler and Sharpton,* 1997): (1) melt-free, typically polymict, **lithic breccias** with a clastic matrix; (2) **melt-fragment breccias** containing fragments of heterogeneous glass, rocks, and minerals in a clastic matrix; (3) melt-matrix breccias **(impact melt breccias)**, composed of rock and mineral fragments in a matrix of glassy or crystalline melt; (4) **impact melt rocks**, composed of glassy or crystalline melt with few or no inclusions (e.g., *Dence,* 1971). Many of these dikes are similar to units of breccia or melt in the crater-fill units above the crater floor, and they may in fact be continuous with them (e.g., *Lambert,* 1981).

Subcrater breccia dikes often contain materials (e.g., rock fragments or melt) that were originally located at higher stratigraphic levels closer to the impact point, indicating that the materials in the dikes have been emplaced downward and/or outward into fractures that opened in the crater floor during formation and modification of the crater. In many structures, more than one generation of dikes occurs, with later ones cutting earlier ones (*Lambert,* 1981; *Dressler and Sharpton,* 1997). These relations indicate that, even during the brief duration (seconds to minutes) of crater formation and modification, a variety of distinct breccia types can be generated and emplaced. However, in the crater environment, cross-cutting relations between breccia bodies do not imply the passage of significant amounts of time between emplacements, a conclusion supported by the fact that the cross-cutting relations between different types of breccia may not be consistent from place to place within the whole structure (*Dressler and Sharpton,* 1997).

Fig. 5.1. Pseudotachylite in granitic gneisses. Pseudotachylite exposure, showing rounded gneiss inclusions from a few centimeters up to a few meters in size in a dense black matrix. The inclusions show a significant amount of rotation relative to each other. Southwest sector of the Vredefort structure (South Africa) (farm Samaria 484). Black pen on large inclusion in center (arrow) is 15 cm long; inclusion itself is about 50 cm long. From *Reimold and Colliston* (1994); photograph courtesy of W. U. Reimold.

5.3.5. Pseudotachylite

Pseudotachylite is an unusual, much-studied, and long-debated type of impactite breccia that occurs in the parautochthonous rocks of large impact structures (for recent reviews, see *Reimold,* 1991, 1995; *Spray,* 1995). Pseudotachylite is most strikingly developed at two large, ancient impact structures: Vredefort (South Africa) (*Shand,* 1916; *Reimold,* 1991; *Reimold and Colliston,* 1994) and Sudbury (Canada) (*Fairbairn and Robson,* 1941; *Speers,* 1957; *Dressler,* 1984; *Thompson and Spray,* 1994; *Spray and Thompson,* 1995), where it forms striking and extensive exposures (Figs. 5.1 and 5.2). The Vredefort pseudotachylite, first described more than 80 years ago (*Shand,* 1916), typically occurs as abundant irregular, anastomosing, and dike-like bodies that contain numerous large and small rounded inclusions of target rock set in a dense, aphanitic or crystalline matrix that is generally black to blackish-green in color. Similar breccias, although developed on a much smaller scale, have been observed in other impact structures, e.g., Rochechouart (France) (*Reimold et al.,* 1987), Manicouagan (Canada) (*Dressler,* 1990), and Slate Islands (Canada) (*Dressler and Sharpton,* 1997).

At Sudbury and Vredefort, pseudotachylite is extensive. Pseudotachylite exposures at Sudbury cover as much as 100–200 km^2, or a few percent of the total area of the structure. Individual pseudotachylite bodies can also be large; the largest body so far recognized at Sudbury is more than 11 km long, more than 400 m wide, and contains discrete fragments that are hundreds of meters in size (*Dressler,* 1984). In smaller impact structures, pseudotachylite bodies are smaller and less abundant; the material typically occurs as irregular dike-like bodies less than a meter across.

The individual pseudotachylite bodies in impact structures are not uniform over long distances and may change size and shape radically within meters or tens of meters. The more elongate dike-like bodies show little or no preferred orientation in direction. The fragment/matrix ratio in

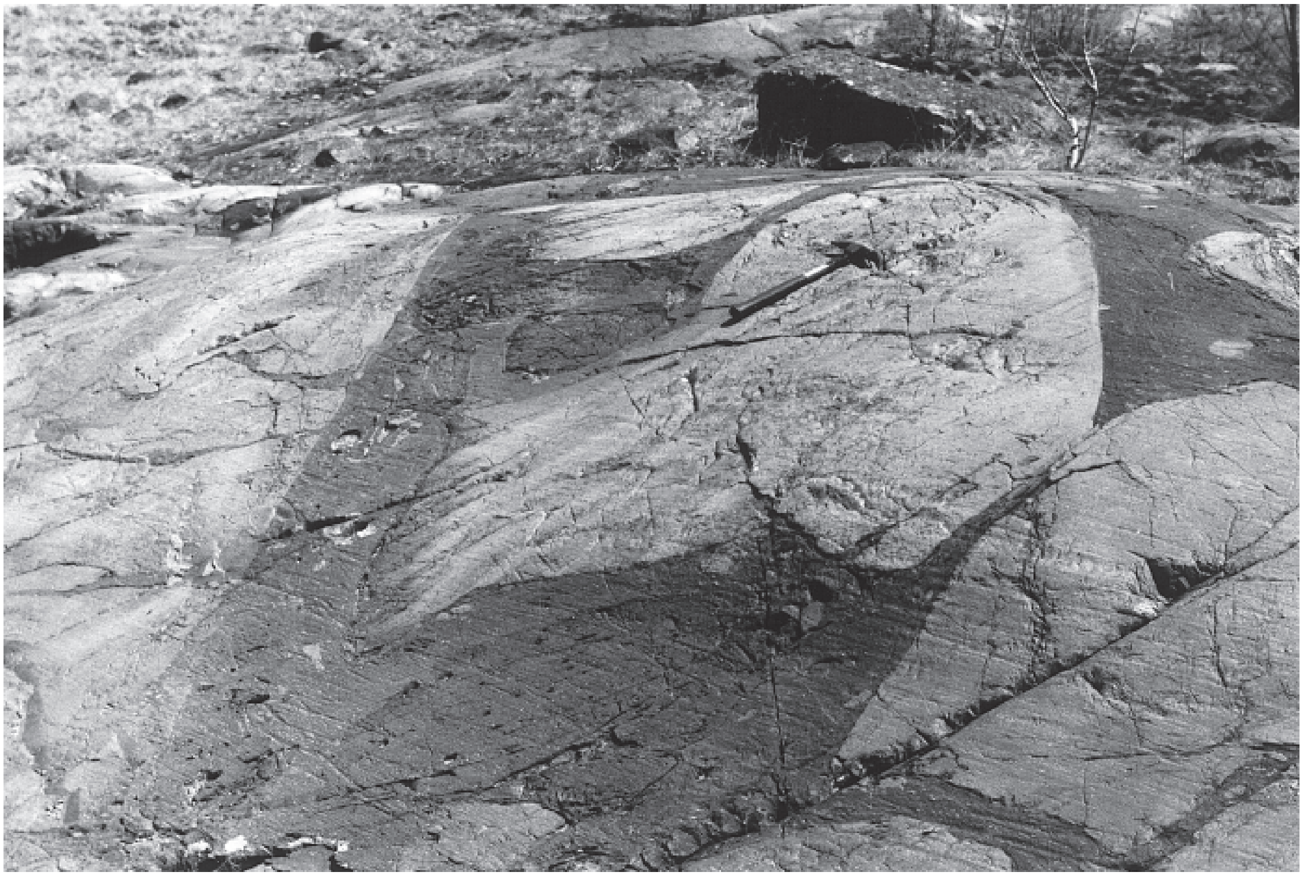

Fig. 5.2. Pseudotachylite; metamorphosed, in quartzite. Dark pseudotachylite ("Sudbury Breccia") in Mississagi Quartzite on South Range of Sudbury structure (Canada). Exposure shows large rounded blocks of quartzite in a pervasive black matrix (note penetration of matrix into large quartzite block at lower right). Hammer (upper right) gives scale. Photograph courtesy of W. Peredery.

pseudotachylite bodies also varies significantly over short distances, and some pseudotachylite breccias consist only of fractured target rocks cut by thin veins of black matrix less than a few millimeters wide. (The descriptive term "**cobweb breccias**" has been used as a convenient field label for such occurrences.)

Contacts between pseudotachylite bodies and the enclosing target rock are irregular and generally not parallel on opposite sides. Offsets of wallrock along pseudotachylite bodies are uncommon, and observed displacements are minor (e.g., <100 m). In very large pseudotachylite bodies with large inclusions, the boundary between the breccia body and the unbrecciated wallrock may not be clear. In such occurrences, e.g., at Sudbury, the exact boundaries between breccia and undisturbed wallrock may be difficult to establish (*Dressler,* 1984).

Inclusions in pseudotachylite range from submicroscopic to hundreds of meters in size. They invariably consist of local bedrock, and there is generally no evidence for significant long-distance (>100 m) transport of fragments during formation. The inclusions are irregularly oriented, and outcrops of the breccia give the strong impression of an overall tensional or explosive environment (Figs. 5.1 and 5.2), rather than the narrower compressional/shear environment that is characteristic of zones of major thrust faulting (*Philpotts,* 1964; *Sibson,* 1975; *Spray,* 1995). Larger inclusions (>1 cm) are generally rounded, while smaller ones tend to be angular or sharp. Contacts between both large and small inclusions and the surrounding matrix are generally sharp. However, some inclusions may be deformed at the rims, forming a flow structure that can be observed, both megascopically and microscopically, to grade into the surrounding matrix (Fig. 5.3).

The matrix between larger rock fragments is dense and coherent. In hand specimen, the matrix often shows a conchoidal or hackly texture on broken surfaces. The color is commonly black to blackish green on fresh surfaces, although the color may vary slightly with the host rock involved. The matrix occurs in a wide variety of forms. It may cover large (meter-sized) areas of inclusion-poor material, or it may form tiny submillimeter filaments that penetrate bedrock and inclusions and often terminate within them. In hand specimen and thin section, the matrix is commonly structureless (Fig. 5.4), but flow-banding is often observed, especially in thin section (Fig. 5.3). This flow-banding may involve inclusions that have been plastically deformed and possibly melted (Fig. 5.5).

The matrix, generally aphanitic in hand specimen, is extremely fine-grained and difficult to characterize, even in thin section. In some samples, the matrix shows definite mi-

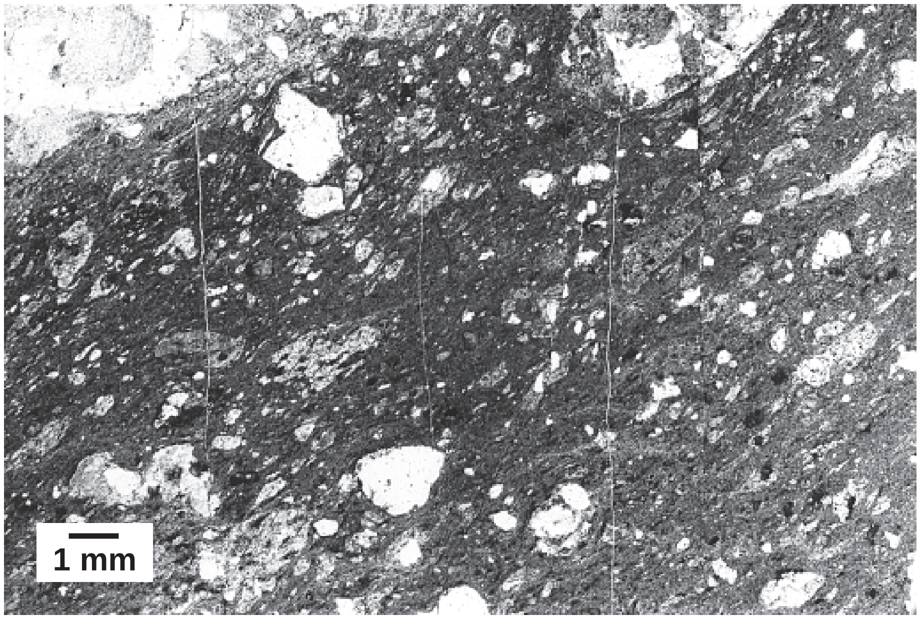

Fig. 5.3. Pseudotachylite; flow-banded texture. Pseudotachylite ("Levack breccia") in granitic gneisses from the North Range of the Sudbury structure (Canada). In thin section, the black pseudotachylite matrix material consists of small irregular rock and mineral inclusions in a dark microcrystalline to aphanitic groundmass. Numerous inclusions (white) show plastic deformation and alignment to form a flow structure; note concentric deformation of the flow structure around larger inclusions (e.g., top right). Thin vertical white lines are filled hairline fractures in the specimen. Sample CSF-67-53 (plane-polarized light).

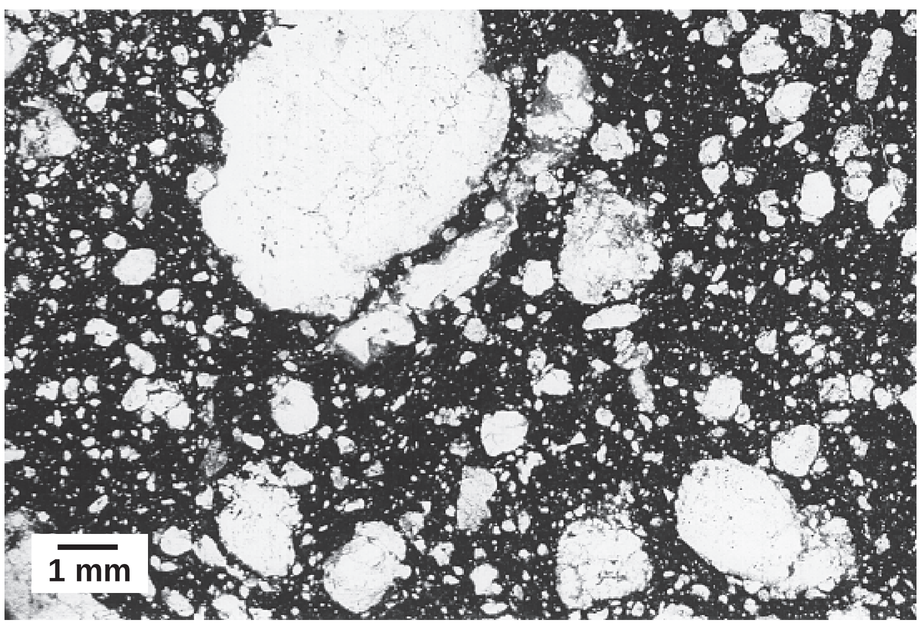

Fig. 5.4. Pseudotachylite; structureless matrix. Pseudotachylite from Vredefort (South Africa), showing typical irregular to rounded inclusions, ranging in size from <100 µm to several millimeters, in a dark aphanitic groundmass. Inclusions, which are rock and mineral fragments from granitic gneisses, show sharp contacts with the matrix. In this pseudotachylite sample, the matrix is structureless, and the inclusions show no deformation, preferred orientation, or other flow structures. Sample AV-81-53 (plane-polarized light).

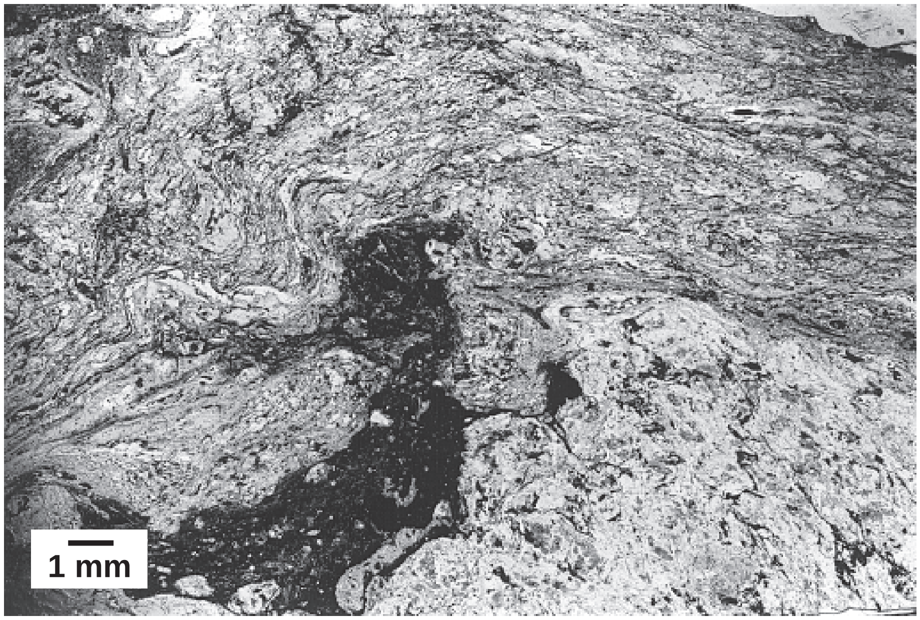

Fig. 5.5. Pseudotachylite; extensive melting and flow. Pseudotachylite ("Levack Breccia") from granitic gneisses in the North Range of the Sudbury structure (Canada). The pseudotachylite consists of a heterogeneous mixture of plastically deformed and possibly melted wallrock fragments (light-colored), mixed with discontinuous areas of more typical pseudotachylite material (dark) consisting of small rock and mineral fragments in a fine black matrix. Sample CSF-88-2A (plane-polarized light).

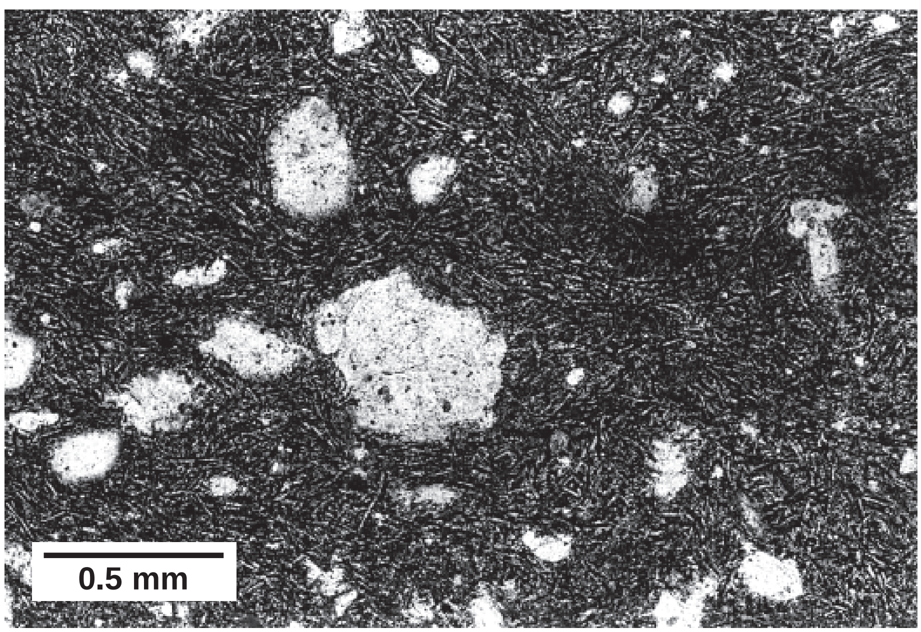

Fig. 5.6. Pseudotachylite; igneous matrix with microlites. Black pseudotachylite developed in central granitic gneisses at Vredefort structure (South Africa), consisting of small, irregular, generally rounded rock and mineral fragments in a black, finely crystalline matrix. Matrix shows igneous flow-banding, expressed by alignment of small feldspar microlites typically 50–100 μm long. The microlites are often concentrically aligned around larger inclusions. Sample AV81-52A (plane-polarized light).

crocrystalline melt textures at SEM or microscopic scales (Fig. 5.6). This characteristic, i.e., a matrix of igneous melt, has been proposed (but not unanimously accepted) as a distinguishing feature of pseudotachylite breccias (*Spray,* 1995). In other samples, the matrix appears to consist of small fragments in a cataclastic texture, and distinguishing between the two types is a difficult process with important implications for both classification and origin (*Reimold,* 1995).

Chemical studies of pseudotachylites (e.g., *Dressler,* 1984; *Reimold,* 1991) have shown that they correspond closely to the adjacent host rocks, indicating that they have formed essentially in place by locally generated cataclastic milling and/or frictional melting processes.

Controversy and debate over the characteristics, terminology, and origin of pseudotachylite has existed ever since the term was first used (*Shand,* 1916) and continues actively today (e.g., *Spray,* 1995; *Reimold,* 1995). *Shand* (1916, pp. 188–189) deliberately coined the word "pseudotachylite" to distinguish the Vredefort material from *tachylite* (basaltic glass) and also from highly crushed and melted materials formed tectonically along major faults (*"flinty crush-rock," ultramylonite, hyalomylonite,* etc.). Unfortunately, Shand's term has since been widely applied to the latter type of material, so that it now designates similar glassy breccias that are clearly tectonic in origin (*Philpotts,* 1964; *Sibson,* 1975; *Reimold,* 1995). Such breccias form in entirely different environments and are the results of intense deformation (including frictional melting) of rocks along the linear trends of faults. They form in a compressional/shear regime, but they can resemble impact-produced pseudotachylite, including the presence of melted material in the matrix (*Philpotts,* 1964).

Recently, some workers have suggested that impact-produced pseudotachylites are formed in the same way as tectonic ones, i.e., by frictional heating during the rapid movements of late-stage crater development and modification (e.g., *Thompson and Spray,* 1994; *Spray,* 1995, 1997; *Spray and Thompson,* 1995). In this view, impact-produced pseudotachylites have essentially the same frictional-melt origin as tectonic ones. One possible way to distinguish between them may be size. Bodies of tectonic pseudotachylite tend to be linear and less than a few meters wide (*Sibson,* 1975; *Spray,* 1995). Impact-produced pseudotachylites, at least at Sudbury and Vredefort, form more irregular bodies, some of which may reach tens to hundreds of meters in size (*Thompson and Spray,* 1994; *Spray and Thompson,* 1995).

Another problem, even within the study of impact-produced breccias, is that the term "pseudotachylite" has been used to designate different types of impact-produced breccias formed at different stages (and possibly by different mechanisms) during crater formation (*Martini,* 1991; *Reimold,* 1995; *Dressler and Sharpton,* 1997). One suggestion (*Martini,* 1991) is to use the term "**type A pseudotachylite**" to designate relatively rare, small, glassy veins, typically less than a centimeter wide, that contain fragments in a matrix of melted material, often accompanied by shock-produced high-pressure mineral polymorphs such as coesite and stishovite (*Martini,* 1991). Such veins are believed to form during the early, higher-pressure, compressive stages of shock-wave expansion. In contrast, the more abundant, widespread, and more intensely studied material (called "**type B pseudotachylite**") is thought (*Martini,* 1991) to form later, during crater modification and central uplift formation, probably by friction generated by the rapid movement of large volumes of target rock below the crater.

Pseudotachylite breccias (especially the more familiar "type B" variety) are distinctive and recognizable at Vredefort and Sudbury, but their wider use as unique indicators of impact is complicated by several factors. First, since they form below the original crater floor, they are found only in impact structures that have been deeply enough eroded to expose target rocks originally located beneath the crater, and pseudotachylites are usually restricted to the central-uplift regions of larger structures. Second, pseudotachylites resemble rocks formed by nonimpact processes, and the distinction is difficult unless definite preserved shock-metamorphic effects can be found. The current confusion in terminology and formation mechanisms, combined with the scarcity of distinctive shock effects in many impact-produced pseudotachylites, makes it difficult to use pseudotachylites by themselves as unique indicators of impact structures.

Despite these problems, well-developed pseudotachylites may still be a useful field tool for identifying possible impact structures for more detailed study. Pseudotachylites can be widespread in impact structures, and their distinctive appearance can survive even high-grade metamorphism (Fig. 5.2). The striking irregular and anastomosing character of pseudotachylite bodies, their rounded inclusions (often altered at the rims), their development over large areas, and the frequent absence of a regular shape or of compressional effects typical of similar fault-related breccias make them a valuable field indicator of a *possible* impact structure, and their discovery should be followed up with an intensive search for more definite shock effects. In addition, melt-rich pseudotachylite breccias in established impact structures have proven valuable for determining the formation ages of the structures themselves (*Spray et al.,* 1995; *Kelley and Spray,* 1997).

5.4. CRATER INTERIOR: CRATER-FILL DEPOSITS (BRECCIAS AND MELT ROCKS)

5.4.1. Formation Conditions

During the modification stage, material excavated from various locations in the growing transient crater is deposited within the final crater to form **crater-fill deposits** of breccia and melt rock. These **allogenic** units consist of four main components: (1) material ejected ballistically on steep or near-vertical trajectories that impacts within the final crater; (2) large and small bodies of impact melt that do not travel beyond the rim of the final crater; (3) large and small fragments of unshocked target rock that collapse from the oversteepened walls and rim of the original transient crater; (4) ejecta originally deposited near the transient crater rim and caught up in the subsequent collapse.

As a result of these processes, the final crater is partially filled with a complex mixture of rock fragments (shocked and unshocked) together with bodies of impact melt. These deposits consist mostly of **crater-fill breccias,** often accompanied by discrete units of **impact melt rocks.** In small, bowl-shaped, simple craters, the various components tend to be mixed together, and the final deposit may fill the crater to about half its depth. [This crater-fill unit is also called the **breccia lens** because of its shape (Fig. 3.7).] In larger complex structures, particularly those formed in crystalline target rocks, the crater-fill rocks typically contain discrete units of breccias and impact melts that form a large annular deposit around the central uplift (Fig. 3.13).

Subsequent to formation of the crater and the deposition of impact-produced **crater-fill breccias,** the structure may be filled, and the breccias buried, by younger **crater-fill sediments** deposited more slowly by the conventional processes of erosion, transport, and deposition. These sediments not only preserve the underlying impact-produced breccias, but, because of their circular outcrop pattern and often anomalous character, they may call attention to previously unsuspected impact structures. In this section, the discussion and the term "crater-fill deposits" are limited only to the impact-produced breccias that fill the crater during and immediately after formation and do not include any ordinary sediments that may also be present.

Many of the individual fragments in the crater-fill deposits have been derived from within the zone of crater excavation (Fig. 3.4) and may be highly shocked. Much of the target rock within the excavation zone is subjected to relatively high shock pressures of about 5 GPa to >100 GPa. The lowest pressures in this range are sufficient to shatter and brecciate the target rocks extensively; at higher pressures, the rocks are deformed and melted as well. Shocked

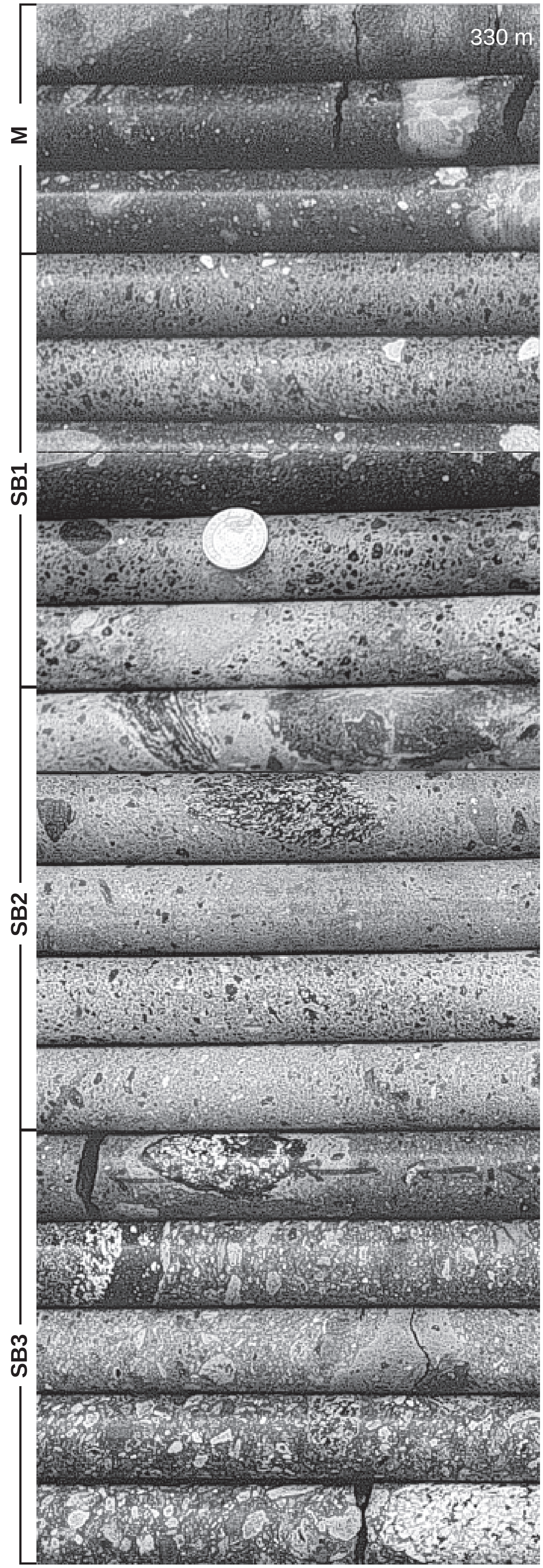

Fig. 5.7. Crater-fill breccias. Recent drill coring along the southern flank of the Chicxulub structure (Mexico), has recovered impact breccias and melt rocks only shallowly buried beneath the younger carbonate sediments. This mosaic shows the sequence of diverse crater-fill breccias retrieved from the UNAM-5 drill core located near the village of Santa Elena in southern Yucatán, ~112 km from the center of the basin. The core pieces are arranged so that each represents 10 m of core. The top of the impact sequence (top of picture) occurs at a depth of ~330 m below the surface and is characterized by a 30-m interval of highly vesicular and pulverized impact melt rock (M). The melt rock horizon is almost completely altered to clay but contains abundant clasts of the target rock assemblage. Below this horizon is a varicolored continuous unit of suevite breccia (SB). As is typical of suevites, this unit has a clastic matrix containing a substantial proportion of highly shocked and melted clasts derived from lithologies that were originally deep within the target assemblage. The upper 50 m of the UNAM-5 suevite (SB1) is characterized by abundant, centimeter-scale clasts of vesicular melt rock, similar to that of the overlying melt horizon but less altered. The middle 50 m of the suevite (SB2) is dominated by larger clasts of shocked to partially melted silicate basement rock showing abundant evidence of shock deformation. The matrix of the lower section of suevite (SB3) is more melt-rich and contains a greater proportion of centimeter-scale silicate clasts. Total depth was reached at the UNAM-5 well while still in the suevite. Coin is ~3 cm in diameter. Photograph courtesy of V. L. Sharpton.

rock fragments, derived from this zone and deposited in the crater-fill breccias, have provided the best evidence for the impact origin of numerous structures.

The crater-filling process is both rapid and chaotic, and mixing of the different components is not complete. The crater-fill deposits therefore contain a variety of distinctive allogenic breccias and melt rocks (Fig. 5.7). The simple classification used below is based on (1) fragment lithologies (lithic vs. melt-fragment breccias; (2) nature of the matrix (clastic vs. melt-matrix). (For more detailed discussions and classifications, see, e.g., *Stöffler et al.,* 1979; *Taylor et al.,* 1991; *Stöffler and Grieve,* 1994, 1996.)

5.4.2. Lithic Breccias (Allogenic)

Melt-free breccias (**lithic breccias**) form a common and distinct lithology in both large and small impact structures (Figs. 3.7 and 3.13). In small impact structures, e.g., Brent (Canada) (*Dence,* 1968; *Grieve and Cintala,* 1981), lithic breccias may form units hundreds of meters thick that extend over much of the final crater. At the larger Ries Crater (Germany), a distinctive allogenic polymict lithic breccia [the **Bunte** (“**colored**”) **Breccia**] occurs beneath the overlying melt-bearing suevite breccias both inside and outside the crater (*Hörz,* 1982; *Hörz et al.,* 1983), with a sharp contact between the two units. In some impact structures, especially those formed in carbonate target rocks, lithic breccias may be the only type of crater-fill material present (*Roddy,* 1968; *Reiff,* 1977).

Lithic breccias consist of rock and mineral fragments in a clastic matrix of finer-grained similar material (Fig. 5.8). The breccias are poorly sorted; fragment sizes generally range from <1 mm to tens of meters. Fragments are typically sharp to angular in appearance. Unlike the lithic breccias found in parautochthonous rocks, crater-fill lithic breccias are more apt to be polymict because their fragments have been derived from a wider region of the original target rocks. Because most of the material in lithic breccias is derived from less-shocked regions around the walls and rim of the transient crater, distinctive shock effects are only rarely observed in the fragments.

Within the crater-fill deposits, lithic breccias are often associated, both horizontally and vertically, with units that contain a melt component as discrete fragments or as a matrix for lithic fragments. Breccias with a few percent or more of a melt component are regarded as **melt-bearing breccias,** but the transition between these breccia types appears continuous, and no formal boundary has been established. Such melt-bearing breccias typically form a smaller proportion of the crater fill, perhaps 10–25 vol%, and the amount of melt component they contain varies from a few percent to >90 vol% (e.g., *Hörz,* 1982; *Masaitis,* 1983; *von Engelhardt,* 1990, 1997).

Two basically different types of melt-bearing breccias can be distinguished. In melt-fragment breccias (**suevites**), the melt component occurs as large (centimeter-sized) discrete bodies; in melt-matrix breccias (**impact melt breccias**), the melt forms a matrix for rock and mineral fragments (*Stöffler and Grieve,* 1994, 1996).

5.4.3. Melt-Fragment Breccias (Allogenic) (Suevites)

Melt-fragment breccias (**suevites**, pronounced “SWAY-vites”) are composed of discrete fragments of rocks and minerals, together with bodies of melt, in a clastic matrix of similar but finer-grained materials. Many of the rock and mineral

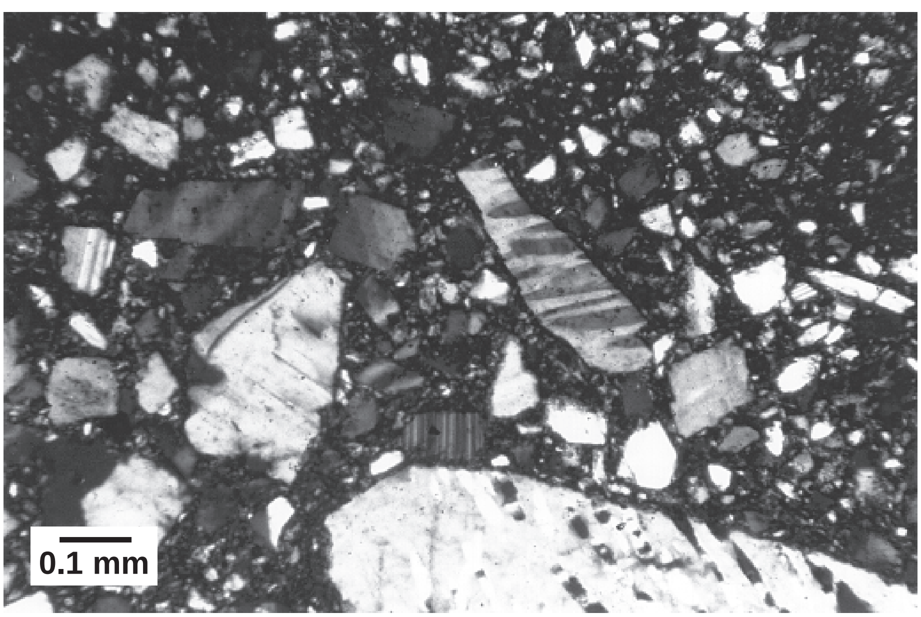

Fig. 5.8. Crater-fill breccia; lithic breccia. Poorly sorted crater-fill lithic breccia composed of angular to sharp fragments of granitic rocks and constituent minerals (quartz, feldspar, etc.) in a finer clastic matrix. Drill core sample from the Brent Crater (Canada). Photograph courtesy of R. A. F. Grieve (cross-polarized light).

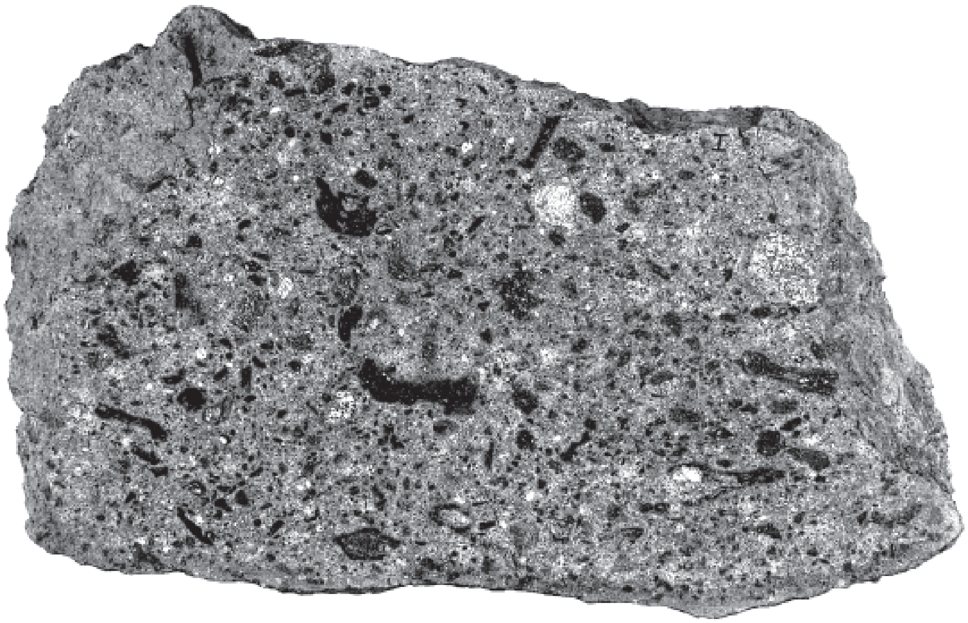

Fig. 5.9. Crater-fill breccia; suevite. Large hand specimen, about 45 cm long, of typical fresh suevite from the Ries Crater (Germany) (Otting quarry). The specimen consists of irregular and contorted individual fragments of glass (dark), which show a roughly parallel elongation, and crystalline rock fragments (light) in a fine clastic matrix. The glass fragments, which range up to 5 cm in size, are composed of a mixture of rock and mineral fragments in heterogeneous, flow-banded glass. Photograph courtesy of D. Stöffler.

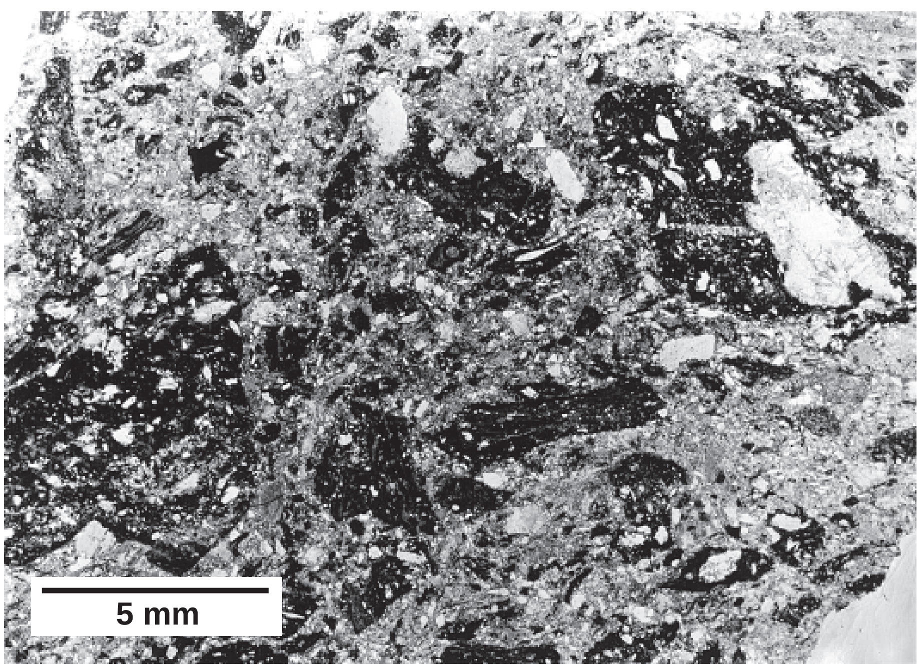

Fig. 5.10. Crater-fill breccia; suevite. Suevite breccia from Nicholson Lake (Canada), containing glass fragments (dark) with rock and mineral clasts in a finer fragmental matrix. The glass fragments are heterogeneous mixtures of mineral clasts (light) in dark, flow-banded glass. Photograph courtesy of M. R. Dence (plane-polarized light).

fragments are highly shocked, and these breccias often provide the most distinctive evidence for a meteorite impact origin of the structures in which they are found.

The term **suevite** was originally applied to melt-fragment breccias from the type occurrence at the Ries Crater (Germany), a relatively young (15 Ma) and well-preserved structure 24 km across, in which well-exposed suevites and other impactites have been extensively studied and drilled (for reviews, see *von Engelhardt et al.,* 1969; *von Engelhardt and Graup,* 1984; *von Engelhardt,* 1990, 1997). Suevite breccias are found both inside the structure (**crater suevite** or **fallback suevite**) and as preserved ejecta deposits (**ejecta** or **fallout suevite**) as far as 40 km from the center of the Ries structure.

Suevite breccias from the Ries Crater and other impact structures typically consist of large (centimeter-sized) and smaller glassy bodies (typically 5–15 vol%), together with rock and mineral clasts in a matrix of finer fragments (Figs. 5.9 and 5.10). Glass-rich suevites are also known, in which the glass fragments may make up >50 vol% of the rock (*Masaitis,* 1994). Individual rock and glass fragments typically range from a maximum size of 10–20 cm down to submillimeter dimensions.

The glassy bodies in the fallout suevite beyond the Ries Crater rim typically show irregular to contorted shapes and textures (*Hörz,* 1965). These bodies are typically heterogeneous, consisting of a polymict mixture of rock and mineral clasts (frequently highly shocked or partially melted) in a matrix of glass that may be compositionally heterogeneous and often shows well-developed flow structure (Fig. 5.11). At the Ries Crater, the larger (5–20 cm) glassy fragments in the ejecta deposits outside the structure, called **Fladen,** show a grooved and lobate flow structure that is evidence of aerodynamic sculpturing during their flight through the atmosphere (*Hörz,* 1965). These bodies also show brittle fractures developed on landing, implying that they were solid when they struck the ground. In contrast, glass bodies in the crater suevite are smaller (normally <5 cm) and lack distinctive sculpturing, implying that they did not travel through the atmosphere for any significant length of time (Fig. 5.12) (*von Engelhardt and Graup,* 1984; *von Engelhardt,* 1990).

Although the Ries suevites are the best-known and most intensely studied examples of this rock type, impressive suevite breccias have been recognized in many other impact structures. However, in many of these structures, erosion has largely removed the ejecta deposits outside the crater, and the suevites occur only as crater-fill units, where they are associated with, and often interbedded with, lithic breccias and impact-melt rocks. Examples include Brent (Canada) (*Dence,* 1965, 1968; *Grieve,* 1978); Rochechouart (France) (*Kraut and French,* 1971); Popigai (Russia) (*Masaitis et al.,* 1980; *Masaitis,* 1994); Manson (Iowa) (*Koeberl and Anderson,* 1996a; *Koeberl et al.,* 1996b); Gardnos (Norway) (*French et al.,* 1997); Slate Islands (Canada) (*Dressler and Sharpton,* 1997); and Roter Kamm (Namibia) (*Reimold et al.,* 1997a). The Onaping Formation, a complex and metamorphosed

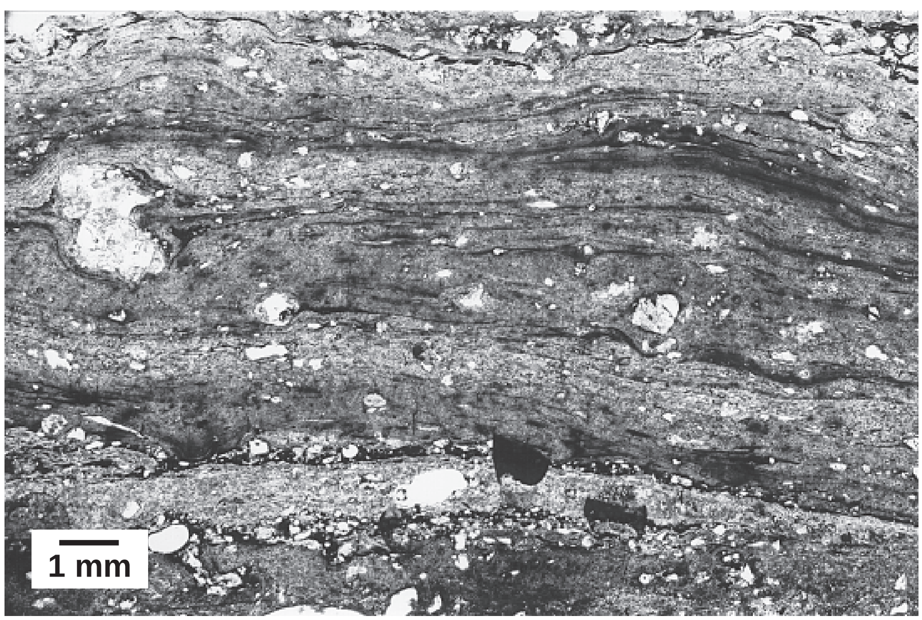

Fig. 5.11. Crater-fill breccia; suevite; glassy inclusion. Heterogeneous, fragment-rich glassy fragment (*Fladen*) in suevite breccia from Lake Mien (Sweden), showing complex, multiple layering with varying amounts of rock and mineral inclusions. The mineral inclusions are typically sharp to angular and do not show the phenocryst shapes that are typically observed in glassy volcanic rocks. The generally laminar flow-banding is emphasized by a sharp difference in clast content and by dark streaks that may represent decomposed and melted opaque minerals. Note that flow-banding in the clast-rich layers (e.g., top) is more highly contorted. Sample NBS-61-0487 (plane-polarized light).

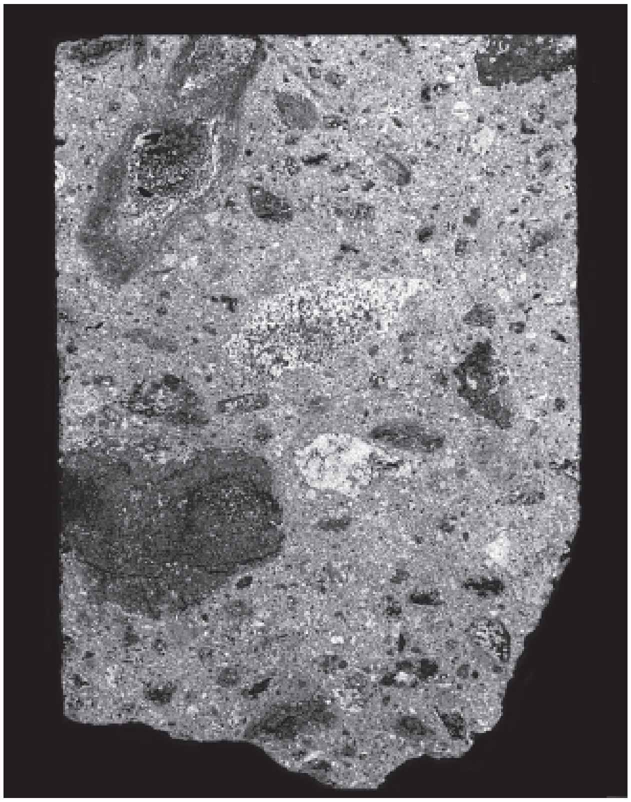

Fig. 5.12. Crater-fill breccia; suevite. Typical poorly sorted suevite breccia in a core sample from the Nördlingen deep drill hole (369.9 m depth), Ries Crater (Germany). The unit contains crystalline rock fragments (light-colored) and glassy fragments (*Fladen*) (dark) in a fine clastic matrix. Inclusion at upper left contains a rock fragment (core) surrounded by a rim of flow-banded glass. Specimen is 10 cm wide. Photograph courtesy of H. Newsom.

crater-fill unit at the 1.85-Ga Sudbury (Canada) impact structure, contains the oldest suevite unit identified so far (Fig. 5.13) (*French,* 1968b; *Muir and Peredery,* 1984; *Avermann,* 1994).

Because of their high melt content and the occurrence of individual glassy bodies, suevite breccias resemble conventional volcanic breccias, and the suevite from the Ries Crater was considered to be a volcanic tuff for nearly two centuries. However, suevites differ from volcanic breccias in several ways, both in hand specimen and microscopically. Fragments in suevites show no volcanic textures; such typical volcanic features as feldspar phenocrysts or corroded quartz phenocrysts are absent (Figs. 5.10, 5.11, 5.14, and 5.15). Rock fragments in suevites are not deep-seated volcanic xenoliths but are derived entirely from the underlying shallow target rocks. Suevites often contain **cored inclusions**, composite fragments in which a rim of glass is wrapped around a fragment of basement rock, indicating that both rock and melt were ejected into the air at the same time (Figs. 5.16, 5.17, and 5.18). Most convincing is the presence of unique high-pressure shock-metamorphic effects (such as PDFs in quartz or the high-pressure minerals coesite and stishovite), in rock and mineral inclusions in the suevite. High-temperature melting effects, e.g., the formation of silica glass (**lechatelierite**) from quartz, may also be present in the glass fragments in suevite.

Despite their widespread distribution, suevite breccias are not found in all meteorite impact structures. In some cases, their absence is probably due to erosion, which has removed these near-surface deposits from the structure. However, the nature of the target rocks also seems important in determining whether suevites are formed (*Kieffer and Simonds,* 1980; *Grieve and Cintala,* 1992). Suevites have so far been observed only in impact structures formed largely or entirely in crystalline silicate rocks, possibly because these rocks melt to produce cohererent and durable bodies of glass. No suevite deposits have yet been found in impact structures formed in carbonate rocks, in which decarbonation and volatile loss, rather than melting, would be important.

5.4.4. Melt-Matrix Breccias (Impact-Melt Breccias)

Suevites inside the crater are closely associated with a different type of melt-bearing breccia: **melt-matrix breccias** or **impact-melt breccias.** In these units, the melt occurs, not as individual fragments, but as a matrix that typically makes up 25–75 vol% of the rock and may range from glassy material to completely crystalline igneous rock. The fragments, which consist of target rocks and minerals, are frequently shocked or melted.

Impact-melt breccias form distinct bodies of widely varying size, from small glassy inclusions in suevite breccias to distinct dike-like and sill-like units tens to hundreds of meters thick. As the melt component increases, impact-melt breccias grade into **impact melt rocks** (see Chapter 6), in which the melt component is dominant and the included fragments are minor or entirely absent. These rocks often have the appearance of conventional igneous rocks.

5.5. CRATER RIM ZONE AND PROXIMAL EJECTA DEPOSITS

The region near the rim of the transient crater is subjected to relatively low shock pressures (typically <1–2 GPa in smaller structures; Fig. 3.4) (*Kieffer and Simonds,* 1980). These pressures are high enough to fracture and brecciate target rocks but are too low to produce unique shock-deformation features in them. The dominant effects in this region are related to the excavation of the crater and the ejection of material from it. In simple craters, which are only slightly larger than the original transient crater, the rim is characterized by structural uplift (and even overturning) of the target rocks that occurs during development of the original transient crater (Fig. 3.3). Even though much of this original transient crater rim may collapse into the final crater during modification, significant uplift may be preserved, especially in smaller and younger craters (e.g., *Shoemaker,* 1963; *Roddy et al.,* 1975; *Roddy,* 1978). Such rim uplift and overturn-

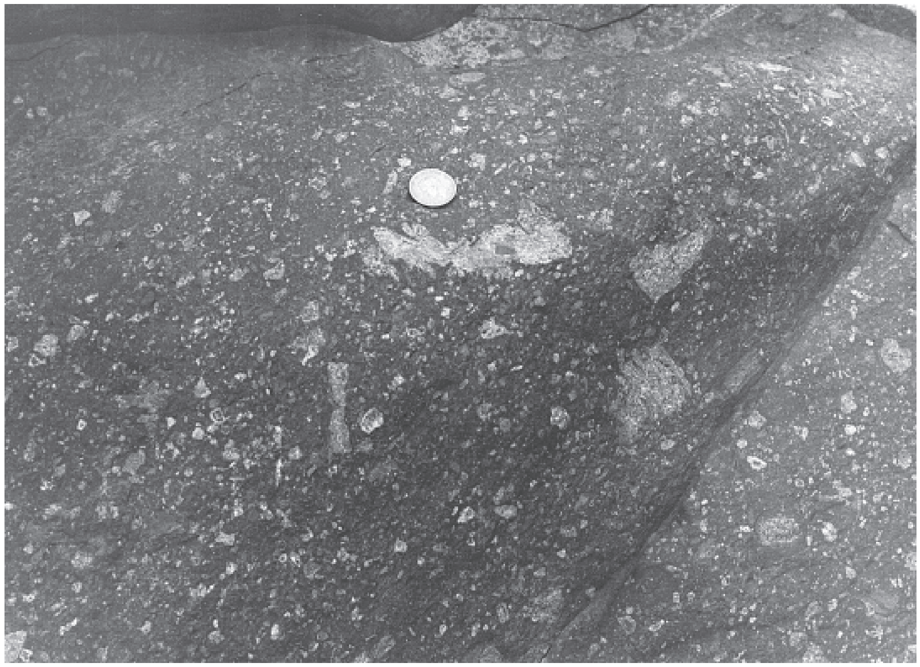

Fig. 5.13. Crater-fill breccia; suevite, metamorphosed. Typical exposure of Onaping Formation "Black Member," showing centimeter-sized fragments of rock fragments and contorted recrystallized glassy inclusions in a black fragmental matrix. Despite color differences, the unit has a strong resemblance to fresh suevite from the Ries Crater (Germany) (see Fig. 5.9). Exposure located at "Black Member" type locality at Onaping Falls (Highway 144, Dowling Township) in the northwestern part of the Sudbury structure (Canada). Diameter of coin near large glassy inclusion is about 2 cm. Photograph courtesy of J. Guy-Bray.

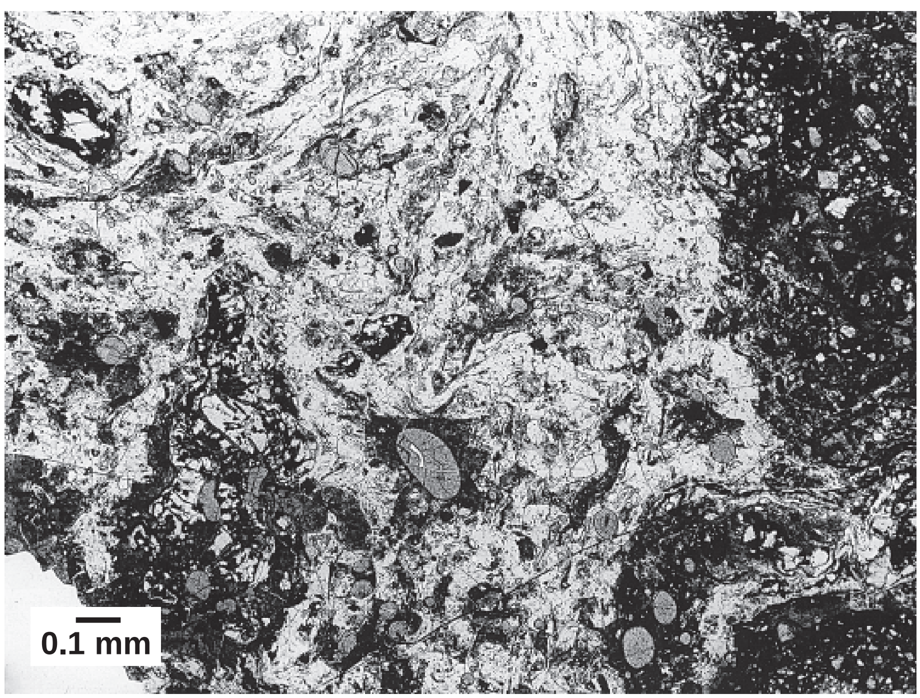

Fig. 5.14. Crater-fill breccia; suevite, heterogeneous glasses. Complex heterogeneous glassy breccia from West Clearwater Lake (Canada), composed of distinct areas of light- and dark-colored mixed glasses, which show short-range turbulent flow and mixing. The glassy areas contain abundant small rock and mineral fragments. Photograph courtesy of M. R. Dence (plane-polarized light).

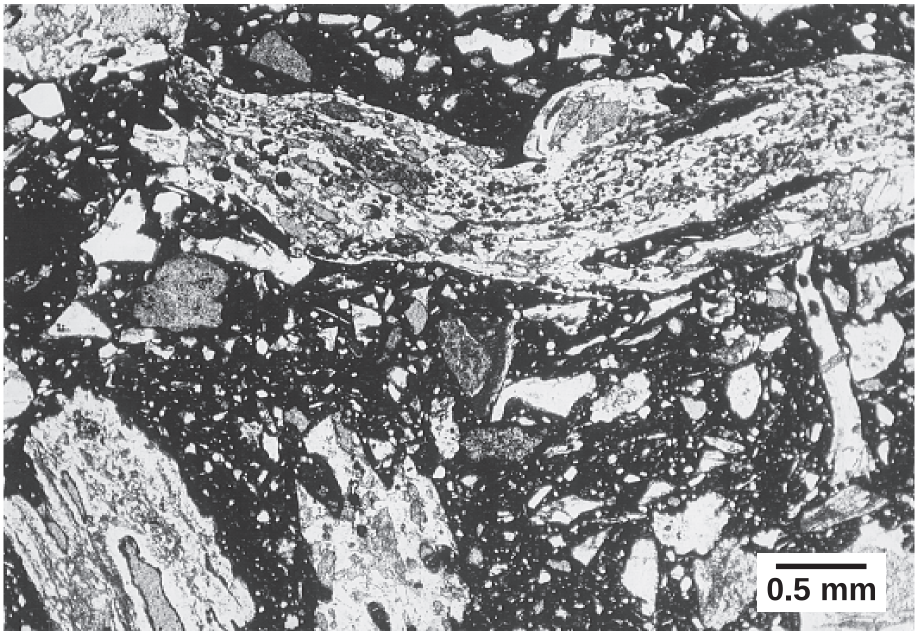

Fig. 5.15. Crater-fill breccia; suevite, metamorphosed. Heterogeneous glassy breccia consisting of fragments of recrystallized glass, together with rock and mineral fragments, in a fine opaque carbon-bearing matrix. Despite greenschist-level metamorphism, the glassy fragments still preserve original melt textures such as flow banding and vesicles (now filled with chlorite; gray). Many of the fragments display sharp crosscutting fractures, indicating that they were cool and brittle when deposited. The rock and mineral clasts represent broken basement (target) rocks; no typical volcanic textures (phenocrysts, etc.) are observed. Discrete fragments as small as 5 μm across can be distinguished in the opaque matrix. Onaping Formation "Black Member," from type locality at Onaping Falls (Highway 144, Dowling Township), northwestern corner of Sudbury structure (Canada). Sample CSF-66-36-1 (plane-polarized light).

Fig. 5.16. Crater-fill breccia; suevite, "cored" inclusion. Large flow-banded fragment (about 15 cm long) from a larger glassy inclusion in the suevite unit of the Ries Crater (Germany) (Bollstadt quarry). The specimen is a composite or "cored" inclusion containing a large block of shocked and fractured crystalline rock (light) surrounded by dark, flow-banded glass. Photograph courtesy of F. Hörz.

Fig. 5.17. Crater-fill breccia; suevite, "cored" inclusion. Composite (cored) inclusion in Onaping Formation "Black Member" in northwestern corner of Sudbury structure (Canada). Inclusion consists of a core fragment of crystalline granitic rock (light-colored) surrounded by flow-banded glassy material, now recrystallized. Similar inclusions are observed in fresher suevite deposits, e.g., at the Ries Crater (Germany) (see Figs. 5.12 and 5.16). A separate angular granitic fragment appears at lower right. Coin at left of inclusion is about 2 cm in diameter. Exposure located at "Black Member" type locality at Onaping Falls (Highway 144, Dowling Township). Photograph courtesy of J. Guy-Bray.

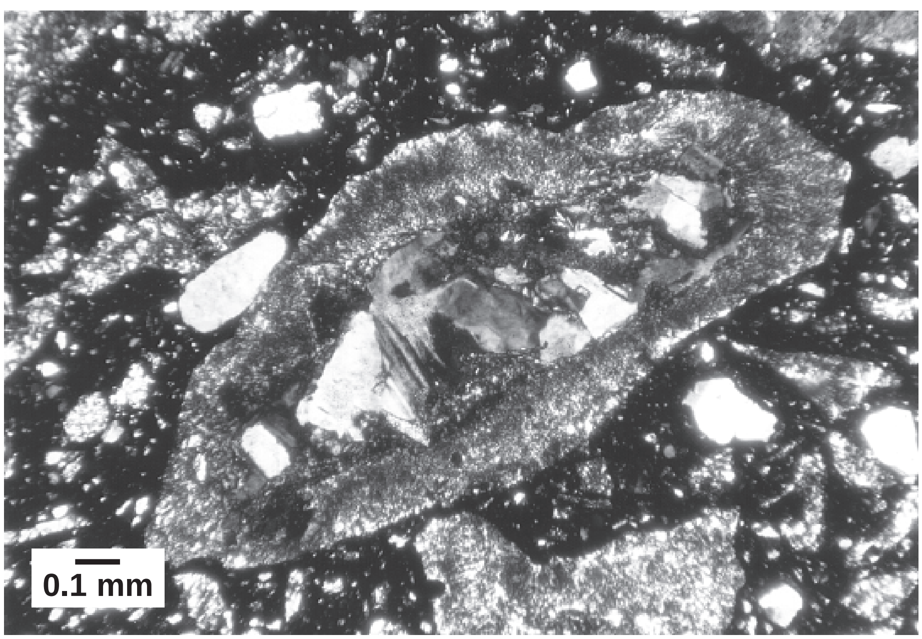

Fig. 5.18. Crater-fill breccia; suevite, "cored" inclusion. Composite rock fragment in metamorphosed suevite unit. The fragment contains a core of fine-grained granitic basement rock surrounded by a rim of microcrystalline recrystallized glass. The fragment is associated with smaller individual clasts of glassy material and rock and mineral fragments in a black, opaque, carbon-bearing matrix. Onaping Formation "Black Member," from type locality at Onaping Falls (Highway 144, Dowling Township), northwestern corner of Sudbury structure (Canada). Sample CSF-66-36-2 (cross-polarized light).

ing are only rarely observed in volcanic explosion structures such as maars and diatremes, and the presence of such rim deformation provides a strong indication of an impact origin for a structure.

In a newly formed crater the rim and the surrounding region are generally covered with allogenic **ejecta** ejected from the growing transient crater (*Melosh,* 1989; Chapter 6). Two kinds of ejecta deposits can be distinguished: those deposited near the crater (**proximal ejecta**) and those distant from the crater (**distal ejecta**).

Most of the material ejected beyond the crater rim is deposited near the crater (*Melosh,* 1989, p. 90). In terms of **crater radius** (R_c, the distance from the center of the crater to the final rim), approximately half the ejecta is deposited within 2 R_c from the center (or 1 R_c from the rim) to form a continuous **ejecta blanket** that may be tens to hundreds of meters thick, depending on the size of the crater. At greater distances, the ejecta unit becomes thinner and increasingly discontinuous; most of the ejecta (>90%) is deposited within about 5 R_c. (This value may serve as an arbitrary boundary between proximal and distal ejecta.) Because many of the fragments in the ejecta deposits were originally close to the impact point, they are often distinctively shocked and melted. Ejecta blankets, where they are preserved, may therefore provide the best and most accessible evidence for an impact origin of the structure.

Ejecta deposits around impact craters are not homogeneous, but are made up of distinct lithologic units derived from different regions of the transient crater and transported by different mechanisms to the site of deposition. Mixing during the ejection and deposition process is not complete, and the ejecta deposits that surround a crater contain the same diversity of rock types that are found as crater fill within the structure: lithic breccias, suevites, and impact melt rocks. In large impact structures, the ejecta deposits preserved outside the crater contain a recognizable sequence of different lithologies. The sequence at the Ries Crater (Germany) (see *von Engelhardt,* 1990, 1997, and references therein) contains a lower unit of polymict lithic melt-free breccia (**Bunte Breccia**) overlain by melt-bearing breccia (**suevite**). Some of the ejecta at the Ries also occurs as large (tens to hundreds of meters in size) limestone blocks ejected intact from the crater and skidded for many kilometers across the surrounding ground surface (*von Engelhardt,* 1990, pp. 264–265).

In impact structures formed on land, the near-surface regions are quickly removed by erosion, and the distinctive rim uplift and ejecta deposits are observed only at relatively young structures such as the Barringer Meteor Crater (Arizona) (age 50 ka) (*Shoemaker,* 1963) and the Ries Crater (Germany) (age 15 Ma) (*von Engelhardt,* 1990). At older structures (e.g., *Dence,* 1965, 1968), distinctively shocked rocks tend to be preserved in only two areas: in the target rocks immediately beneath the crater floor, and in the breccia and melt deposits that fill the crater itself.

5.6. DISTAL EJECTA

Although most of the material (about 90 vol%) ejected from the crater is deposited relatively close (<5 R_c) to the crater (*Melosh,* 1989, p. 90), a significant amount (about 10 vol%) may travel to even greater distances (>5 R_c) to form deposits of **distal ejecta**. Where an atmosphere is present, as in terrestrial impact events, a combination of disruption of the atmosphere by the impact fireball, ballistic ejection from the crater, and subsequent atmospheric transport can distribute the smaller ejecta particles (typically ≤1 mm) to regional or even global distances (*Alvarez et al.,* 1995). The resulting deposits, usually less than a few centimeters thick, may contain distinctive evidence for impact: shocked rock and mineral fragments, distinctive chemical and isotopic signatures, and unusual glassy objects. It has thus become possible to recognize debris from a given impact structure over a large area of Earth, and even to establish the existence of a major impact event from a globally distributed ejecta layer before the structure itself could be located.

Although few layers of distal ejecta have been identified, they have been critical to recognizing large impact structures and determining their age. Coarse ejecta (millimeter- to centimeter-sized fragments) from the Acraman structure (Australia) (D = 90 km) has been recognized as a discrete layer several centimeters thick at distances of 300–400 km from the site (*Gostin et al.,* 1986; *Williams,* 1986). Ejecta from the Manson structure (Iowa) (D = 36 km) has been recognized more than 250 km away (*Izett et al.,* 1993). The most striking and best-known example of distal ejecta is the thin layer of material ejected from the Chicxulub structure (Mexico) and distributed worldwide to form the K/T boundary layer (*Alvarez et al.,* 1980; papers in *Sharpton and Ward,* 1990, and in *Ryder et al.,* 1996). The occurrence in this layer of shocked quartz grains and small spherules of melted target rock, accompanied by an anomalously high content of the element iridium (derived from the projectile), provided conclusive evidence that a large meteorite impact had occurred at the end of the Cretaceous Period, even before the Chicxulub impact structure itself was identified. The layer also provided key geochemical and geochronological evidence to demonstrate that the Chicxulub structure was identical in age to the K/T boundary and that it was also the source for the global ejecta layer itself.

Generally, ejecta found at greater distances from the crater displays a higher level of shock effects, and much distal ejecta consists of small fragments of melted target rock. One peculiar and much-studied variety of distal ejecta is **tektites** and **microtektites**, small (centimeter- to millimeter-sized) bodies of pure glass that have been ejected from a few impact structures and spread over areas (**strewnfields**) that may be thousands of kilometers in extent (see Chapter 6).